

Mode dispersion and photonic storage in planar defects within Bragg stacks of photonic crystal slabs

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It is shown that electromagnetic energy can be localized to defect regions bounded by parallel planar walls perpendicular to the stack surface in Bragg stacks of two-dimensional photonic crystals. These regions produce larger bandgaps than single-photonic-crystal slabs. Group velocity and dispersion relations can easily be tailored by choice of the proper geometry and materials. Results indicate that such photonic crystals might facilitate photonic trapping and storage together with advanced photonic manipulations. © 2004 Optical Society of America

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1. INTRODUCTION

Photonic crystals (PCs) made from dielectric materials are structures with spatially periodic variations of their dielectric constants. It has been suggested that photons in subwavelength periodic dielectric structures might be controlled in much the same way as electrons are in a periodic electrical potential of atoms and molecules in a crystal lattice of a semiconductor material.^{1,2} In the past decade scientific effort has clarified some of the remarkable properties of one-, two-, and three-dimensional PCs through extensive theoretical and numerical studies³ and through experimental validation.^{4–7} Theoretical studies indicate that PCs and cavity defects within PCs might produce new, improved optical functions such as optical detection, emulation of metamaterials, and superlensing with point imaging below the diffraction limit of classical lenses owing to negative refraction.^{8–12}

Electromagnetic energy can be localized to channel defects and point defects within PCs with unit cells of a true three-dimensional (3D) nature with a complex material distribution, producing complete bandgaps for all directions of propagation and all polarization states.^{13,14} However, it is difficult to produce these structures with current techniques because complicated 3D alignment and advanced repetitive chemical and physical processes are needed. Other 3D PCs based on a layer-by-layer building approach in which each layer exhibits only a two-dimensional (2D) complexity have been proposed.^{15,16} A few repetitions of these PCs' unit cells would suffice to significantly suppress radiation. Unfortunately, precise 2D alignment between layers is still needed, together with costly multiple repetitive chemical processes and planarizations to prevent unintentional defects that would permit leakage of energy. PC slabs are far simpler structures that rely on high-index confinement in the vertical direction.^{17,18} These structures exhibit pseudobandgaps and therefore permit significant radiation leaks to occur in line defect waveguide bends.⁶ Ways to minimize

leakage of energy by surrounding PC slabs with planar one-dimensional (1D) omnidirectional stacks or other slabs of specific heights have been proposed.¹⁹ All these solutions attempt to decrease the number of intrinsic radiation states in the waveguide surroundings or to increase their reflectivity for a large set of angles and polarizations. Recent theoretical and numerical investigations have shown that another, quite simple crystal, a planar multilayer stack of 2D PCs (planar MS2DPC) that lacks complete 3D bandgaps, can exhibit full in-plane bandgaps and under certain conditions can exhibit a region of omnidirectional reflection for air defects²⁰ that cannot be achieved with PC slabs or PC slabs surrounded by 1D stacks.

One type of multilayer stack of 2D PCs (MS2DPC1) is made from a 1D dielectric multilayer stack in the $\hat{z}$ direction (Fig. 1). The stack consists of alternating planar layers of materials A and B, in which a 2D crystal lattice of cylindrical holes is etched that might be filled with material C.²⁰ The 1D structure suppresses electromagnetic modes of radiation propagating along the z axis, while the 2D structure suppresses electromagnetic modes of radiation propagating along directions within the xy plane, i.e., parallel to the layer surfaces in the stack. The 1D periodicity along the z axis is characterized by $\Lambda_z = t_{Az} + t_{Bz}$, where t_{Az} and t_{Bz} are the respective layer thicknesses. The 2D crystal lattice is characterized by the nature of the lattice (square, triangular, honeycomb, ...), the 2D lattice constant Λ , and the material distribution in the spatial unit cell. We focus on circular cylindric holes. We define r_0 to be the radius of the filled cylinders and denote by n_A , n_B , and n_C the respective refractive indices and by $N_z\Lambda_z$ the total height of these structures. The following theoretical and numerical investigations relate to structures for which N_z is infinite to facilitate an understanding of the general electrodynamics. In real structures N_z is finite, and this number needs to be sufficiently high to produce strong localization. Future inves-

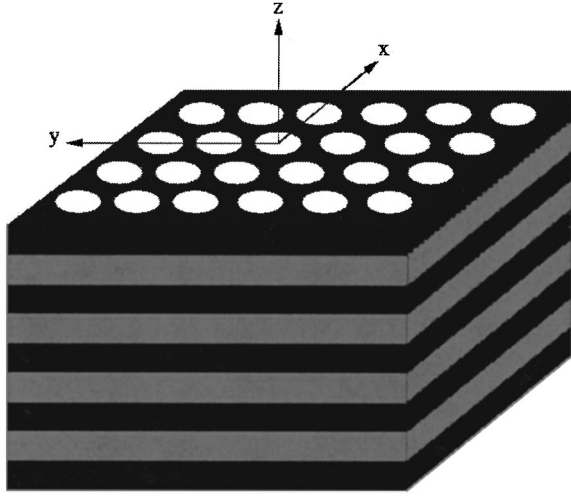


Fig. 1. Multilayer stack of 2D PCs (MS2DPC1) made from a 1D dielectric multilayer stack in the $\hat{z}$ direction. The stack consists of alternating planar layers of materials A and B, respectively, in which a 2D crystal lattice of cylindrical holes is etched that these might be filled with material C.

tigations will clarify this issue. N_z may need to be large if the index contrast of the stack is small.

The electrostatics in a MS2DPC depends on polarization of the field.²⁰ We can estimate the fraction of the total average electric energy stored in the z component of the electric flux density $\mathbf{D}$ in space by computing

$$f_{E_z} = \frac{\iiint |\mathbf{D} \cdot \hat{\mathbf{z}}|^2 d\mathbf{r}}{\iiint |\mathbf{D}|^2 d\mathbf{r}} \quad (1)$$

for all eigenstates. We denote by P_1 modes that have $f_{E_z} < 0.1$ in the numerical analysis (TE modes for $k_z = 0$ belong to this category). TE-like modes in conventional waveguides with optical axes parallel to the xy plane belong to the P_1 group. Modes with other polarizations or energy distributions are referred to as P_2 modes.

It might be easier to manufacture Bragg stacks of PC slabs than most 3D PCs, and Bragg stacks do exhibit large in-plane bandgaps. We want to characterize cavities within them in the hope that they can facilitate photonic storage, strong dispersion, and interesting optical signal processing with minimal radiation loss. In this paper we analyze electromagnetic states localized to planar defects bounded by parallel planar walls perpendicular to the surface of the stack in a MS2DPC of infinite height with a triangular lattice of circularly cylindrical holes filled with air. In Section 2 planar defect types and computational issues are discussed. Section 3 concerns planar defects created by varying the radii of holes along one row in different directions. A discussion of in-plane propagation and confinement in symmetric waveguides in the xy plane is given in Section 4. The consequences of in-plane symmetry breaking are discussed in Section 5, and it is indicated that 2D alignment errors in the production can have negative effects on the waveguiding properties. Concluding remarks are given in Section 6.

2. DISCUSSION OF DEFECT TYPES AND COMPUTATIONAL ISSUES

We use a freely available software package for photonic band calculation by employing preconditioned conjugate-gradient minimization of the Rayleigh quotient in a plane-wave basis.²¹ Figure 2 shows a 2D view of the MS2DPC1 structure in the absence of defects. In the xy plane the normalized vectors $\mathbf{a}_1' = 2\pi[(\sqrt{3}/2)\hat{\mathbf{x}} - 1/2\hat{\mathbf{y}}]$ and $\mathbf{a}_2' = 2\pi[(\sqrt{3}/2)\hat{\mathbf{x}} + 1/2\hat{\mathbf{y}}]$ define the 2D lattice of air holes, and $\Lambda_1 = \sqrt{3}\Lambda$ and $\Lambda_2 = \Lambda$. We may categorize planar defects into three main types. We denote by D^{xy} (xy -plane defects), D^{xz} (xz -plane defects), and D^{yz} (yz -plane defects) the set of planar defects geometrically restricted to $|z| < h_D/2$, $|y| < W_D/2$, and $|x| < W_D/2$, respectively, where h_D is the height of the defect region and W_D is the width of the defect region surrounded by the bulk MS2DPC (we use the boldface $\mathbf{D}$ for the field vector and the italic D for defect references). The latter two types are analyzed in what follows, whereas the first one requires special attention, which I intend to address in a future publication.

To investigate defect modes we employ a supercell approach. A supercell covering many unit cells of the perfect MS2DPC1 crystal is spatially repeated in a lattice with normalized lattice vectors $\mathbf{a}_i = 2\pi(N_i + 1)\Lambda_i/\Lambda\hat{\mathbf{i}}$, where $i = 1, 2, 3$ represent the x, y , and z components, respectively, and N_i are whole numbers. The relevant part of the resultant Brillouin zone (BZ) is determined by $0 \leq k_i \leq 0.5|\mathbf{b}_i|$, where $\mathbf{b}_i = \Lambda/[(N_i + 1)\Lambda_i]\hat{\mathbf{i}}$ is the normalized reciprocal lattice vector. The MS2DPC1 that we study exhibits full 2D bandgaps for $k_z = 0$, independently of the direction of in-plane propagation, whereas the bandgap has a strong k_z dependency, and suppression of out-of-plane scattering modes is best for $\Lambda_z/\Lambda < 1$, with $1/\Lambda_z$ determining the height of the BZ for the perfect crystal with one unit cell. If Λ_z/Λ is too large, the regions of

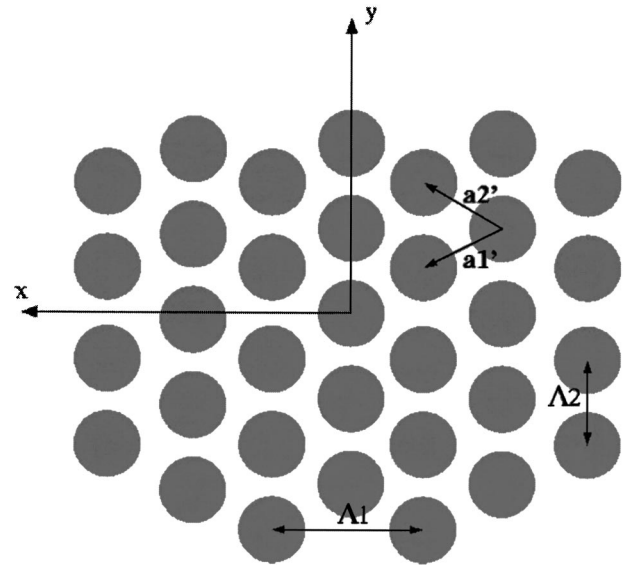


Fig. 2. 2D view of the MS2DPC1 structure under investigation in the absence of defects. In the xy plane the vectors $\mathbf{a}_1' = 2\pi[(\sqrt{3}/2)\hat{\mathbf{x}} - 1/2\hat{\mathbf{y}}]$ and $\mathbf{a}_2' = 2\pi[(\sqrt{3}/2)\hat{\mathbf{x}} + 1/2\hat{\mathbf{y}}]$ define the 2D lattice of air holes, while $\Lambda_1 = \sqrt{3}\Lambda$ and $\Lambda_2 = \Lambda$.

forbidden modes are greatly reduced and can disappear as wave number k_z is subjected to scaling, and the height of the BZ tends to zero. This means that the supercell approach must be used with care in the analysis of defects of type D^{xy} because as N_3 is varied from zero to infinity the extent of the supercell BZ vanishes; i.e., the range of wave number k_3 tends to zero as the BZ is folded down many times, creating an artificial periodicity. Wave number k_3 in the supercell approach with the defect is not identical to original wave number k_z when the band structure of the perfect MS2DPC is computed with one unit cell. In this paper we study the D^{xz} and D^{yz} defect types. We set $N_3 = 0$; N_1 and N_2 are chosen as even numbers.

We create one of the defects that we study by changing the size of the radius of the hole in a row along the y axis in the MS2DPC1 structure under investigation (yz -plane defect). In this case we choose $N_2 = 0$. Ideally N_1 is infinite and $k_x = 0$, but these values cause the height of the original BZ to be folded N_1 times into the supercell's BZ, increasing the number of radiation modes that need to be computed. We need to determine an appropriate finite value of N_1 to permit a computation of defect states. In this approach radiation states (nonlocalized states) have frequencies and modes that vary with N_1 , whereas such is not the case for electromagnetic states localized to the defect region once a reasonable PC wall thickness is found. N_1 is increased until the latter criterion is satisfied. Similar considerations are made for other types of planar defect. In what follows, projected bands that correspond to nonlocalized radiation states are computed in a supercell from which the defects are removed to facilitate a better relative identification of defect states.

We focus on defect types D_s^{xz} (D_s^{yz}), which refer to a defect in the xz (yz) plane and for which the subscript s denotes the structural nature of the defect. $\uparrow\bigcirc$ and $\downarrow\bigcirc$ denote defects where the radius r_D of a row of holes along the x (y) axis is increased or decreased, respectively, in the otherwise perfect PC (reduced index or increased index defects). Furthermore, $\parallel$ denotes a planar defect where a layer of material with refractive index n_D is introduced into a region determined by $|y| \leq W_D/2$ for D^{xz} defects, and by $|x| \leq W_D/2$ for D^{yz} defects, in the multilayer stack before the lattice of holes is etched in the structure, where W_D is the width of the center layer with refractive index n_D as shown by the lighter-gray areas in Fig. 3 ($D_{\parallel}^{yz}$, a defect where all holes have the same radius). There is of course a multitude of defect types, but the defects of types $D_{\uparrow\bigcirc}^{xz}$, $D_{\downarrow\bigcirc}^{xz}$, $D_{\parallel}^{xz}$, $D_{\uparrow\bigcirc}^{yz}$, $D_{\downarrow\bigcirc}^{yz}$, and $D_{\parallel}^{yz}$ are achievable and general. By studying these defects we can increase our understanding of the localization of electromagnetic radiation in 3D space to control the energy flow in a relatively simple crystal. These defects also give a good indication of the potential of light localization in channel and point defects in a MS2DPC.

To determine the energy confinement in a region about the defect we estimate that

$$\mathcal{E}_C^{\mathcal{W}} = \frac{1}{2} \left(\frac{\int_V \mathbf{D} \cdot \mathbf{D} dv}{\langle \mathbf{D} | \mathbf{D} \rangle} + \frac{\int_V \mathbf{H} \cdot \mathbf{H} dv}{\langle \mathbf{H} | \mathbf{H} \rangle} \right),$$

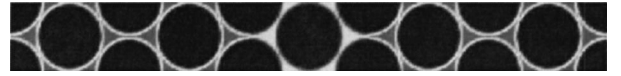


Fig. 3. 2D view of the supercell with a yz -plane defect in the MS2DPC1 structure under investigation. This $D_{\parallel}^{yz}$ defect is created by introduction of a layer of material with refractive index n_D into a region determined by $|x| \leq W_D/2$ in the multilayer stack before the lattice of holes is etched in the structure, where W_D is the width of the layer (all holes have the same radius).

which represents the fraction of the average total energy in the fields located in a volume within the supercell restricted to $|y| \leq W/2$ for D^{xz} defects ($|x| \leq W/2$ for D^{yz} defects), where W is the chosen extent along the y axis (the x axis for D^{yz} defects). Typically, $W = W_D$.

Some important properties of PCs are their ability to manipulate the group velocity:

$$\frac{\mathbf{v}_g}{c} = \frac{\nabla_{\mathbf{k}} \omega}{c}, \quad (2)$$

where c is the velocity of light in vacuum, and the normalized dispersion of electromagnetic fields:

$$\mathbf{D}c\lambda = -\omega \frac{\partial^2 \mathbf{k}}{\partial \omega^2}. \quad (3)$$

A mode experiences dispersion because of the various effective refractive indices along different directions of propagation, depending on the order of the mode (ground mode or higher-order modes), their polarization, frequency, and field distribution or degree of localization. The dispersion comes mainly from two sources: the waveguide dispersion that is due mainly to the geometry of the planar defect waveguide and the bulk refractive indices in the homogeneous layers of the cladding and defect region, and finally the material dispersion that is due to the wavelength dependence of the refractive indices related to vibrational resonances, electronic excitations, and absorption peaks in electrically polarizable molecules and atoms. We do not consider temperature effects on the carrier density in the different layers with homogeneous material, and we disregard the wavelength dependence of the refractive indices in the study presented here. We assume for simplicity that they are locally constant in the wavelength range of interest. We also assume that the materials with which we work are ideally lossless; i.e., surface roughness and material impurity induced scattering and absorption are minimal. The materials in their bulk form are assumed to be homogeneous and isotropic (amorphous), yielding a constant macroscopic refractive-index distribution. We also disregard any nonlinear phenomenon for simplicity in the present investigation in which the interaction of radiation with matter is considered in the linear regime. In real structures with a finite number of layers a little dissipation of energy occurs because modes are allowed to radiate energy as photons can leak through a reduced potential barrier. This dissipation depends strongly on the order of the mode, its frequency and confinement, and its polarization, similarly to those in omniguide fibers.^{22,23}

3. PLANAR DEFECTS CREATED BY VARYING THE DEFECT RADIUS

In this section we discuss the planar defects in the defect-free structure of Fig. 2 in a previously published study.²⁰ Figure 4 shows band diagrams for propagation along the y axis only [Fig. 4(a)], at some oblique axis in the yz plane along $(\mathbf{b}_2 + \mathbf{b}_3)$ [Fig. 4(b)], and along the z axis only [Fig. 4(c)] for a D_{10}^{yz} defect with $r_D = 0.5\Lambda$. In each case the white region represents the polarization-independent bandgap for the indicated particular propagation directions for MS2DPC1 in the absence of defects. The region formed by the union of the lighter-gray region and the white region is a region that is forbidden to P_1 states. The polarization-dependent bandgap of MS2DPC1 is re-

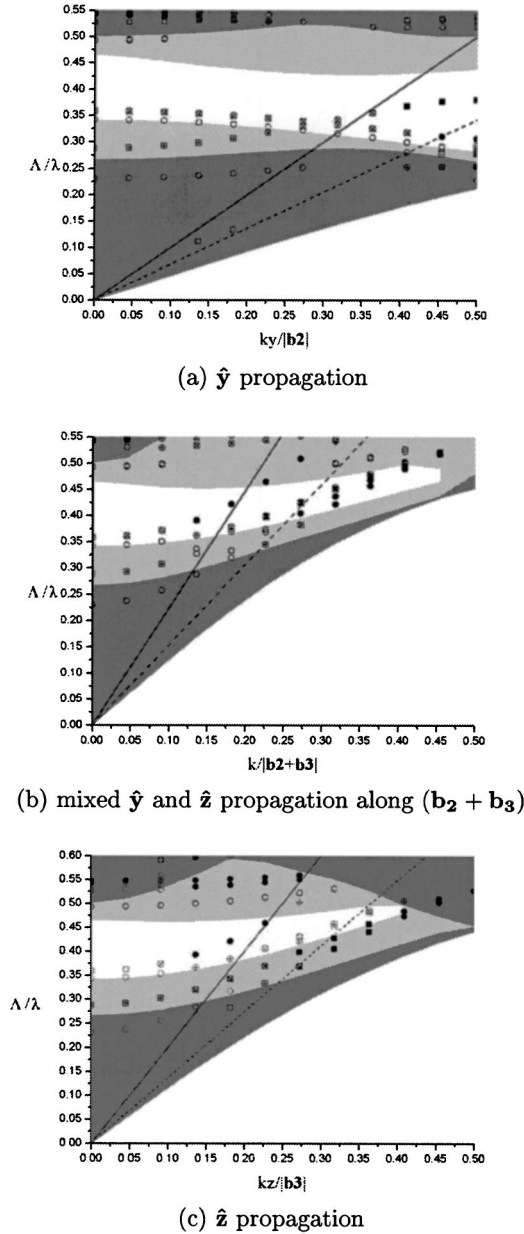


Fig. 4. Band diagrams for propagation (a) along the y axis only, (b) with some oblique axis in the yz plane along $(\mathbf{b}_2 + \mathbf{b}_3)$, and (c) along the z axis only for a D_{10}^{yz} defect with $r_D = 0.5\Lambda$.

lated to P_1 states. A continuum of electromagnetic states is allowed in the defectless MS2DPC1 in the darker-gray region of the band diagram where modes are mainly non-localized (radiation states) and generally polarized. Note that we focus only on the main bandgaps and for clarity do not show smaller pseudogap regions. The presence of numerous narrow pseudogaps indicates a locally decreased density of states in this condensed matter that is due to the local suppression of radiation states $(\mathbf{k}, \omega)$. The air line is a black solid line; the SiO_2 line is a dashed line. Localized P_1/P_2 modes are symbolically labeled according to different levels of energy confinement in a region in the vicinity of the defect determined by $|x| \leq W/2$, where $W = \sqrt{3}\Lambda$: $30\% \leq \mathcal{E}_C^{\text{SiO}_2} \leq 50\%$ ($\square/\circ$), $50\% \leq \mathcal{E}_C^{\text{SiO}_2} \leq 70\%$ ($\boxplus/\oplus$), $70\% \leq \mathcal{E}_C^{\text{SiO}_2} \leq 90\%$ ($\boxtimes/\otimes$), and $90\% \leq \mathcal{E}_C^{\text{SiO}_2} \leq 100\%$ ($\blacksquare/\bullet$). We disregard modes with the lowest energy localization, as these are more lossy. The above convention for presentation concerns all the band diagrams that follow in this section. Note that the bandgap regions for propagation along a single axis can be larger than those relative to several directions or planes. It is, however, the aforementioned main bandgaps (polarization-dependent or -independent) that are the most important because radiation at these frequencies is trapped in the defects of the bulk crystal, which acts as a high- Q cavity of finite extent. In Fig. 4 the defect is a reduced index defect. For $\hat{y}$ -parallel propagation a single P_1 state seems to be strongly confined and localized to the bandgap region. It emerges out of the lower bandgap boundary. When $|r_D - r_0|/r_0 \sim 0$ at the point where single-mode operation is permitted in the defect, the localized fundamental mode has a higher effective index than the radiation states on the upper gap edge, and, because the effective index of the defect material is lower than in the surrounding crystal, the localized defect state emerges therefore at the lower gap edge and is pulled up into the bandgap. Increasing the defect radius allows this defect state to propagate along the waveguide with better energy confinement, experiencing a lower effective index with a frequency band that moves upward into the gap. This P_1 defect state $\omega_D(k_y)$ experiences stronger energy confinement with increasing wave number k_y because $\omega_D(k_y)$ moves toward the middle of the bandgap where the gap-to-radiation state is greatest at the center of the photonic potential well. The effective index relative to the y axis, $n_{\text{eff},y}$, that this defect state experiences falls with larger k_y values with which the mode has a weaker experience of the cladding and better energy confinement in the low-dielectric region. The highest energy confinement is obtained when $\omega_D(k_y)$ reaches a dielectric line between the light line and the SiO_2 line that corresponds to the maximal effective index of the material in the defect region. Two P_2 -mode defect states are also present in the polarization-independent bandgap. That with the highest $n_{\text{eff},y}$ has better energy confinement. These two P_2 states lie close to each other. For P_2 -mode defect states $n_{\text{eff},y}$ falls with increasing k_y , unlike in the P_1 mode. This difference can be explained by the different directional effective indices experienced by different polarization components. It is clear that one can design a frequency interval for single-mode propagation by tuning defect radius r_D . This fact is important for energy

transport with low dispersion and uniform effective energy-propagation velocities. It can also be observed from Fig. 4(a) that other localized states occur in regions with small pseudobandgaps. Figure 4(b) illustrates propagation along a direction parallel to $\mathbf{b}_2 + \mathbf{b}_3$, where $\mathbf{b}_2 = \hat{\mathbf{y}}$ and $\mathbf{b}_3 = \Lambda/\Lambda_z \hat{\mathbf{z}}$ are two of the normalized reciprocal lattice vectors. Propagation of localized states in this direction happens mainly in P_2 modes because of the many dielectric interfaces encountered and the different propagating angles that yield many possible effective indices for localized states of general polarization. The defect functions as a multimode waveguide. Figure 4(c) illustrates propagation along the z axis only. There are three localized P_2 modes and two localized P_1 modes. Their dispersion properties are quite different, depending on their positions in the bandgap and their degrees of confinement. Results show that localized modes occur also in smaller pseudogap regions above the main bandgap. Figure 4 indicates that radiation might be guided efficiently in z -invariant channel defects.

Figure 5 shows a band diagram for propagation along the y axis only for a D_{10}^{yz} defect with $r_D = 0.45\Lambda$, an increased index defect. One of the major differences between increased and reduced index defects is the appearance in the former of guided modes whose localization is due to pseudogaps near the light line where fields are localized to high-index regions in a manner that is similar to that for total internal reflection, where radiation is classically confined to the region of high refractive index. These defect modes appear near the lower boundary or light line of the darker-gray region that represents the set of nonlocalized modes. It is important to note that the light line for P_1 states is not necessarily the same as the light line for P_2 states, a fact that to minimize complexity is not illustrated on Fig. 5. There are two strongly localized defect states that propagate under their respective light lines. For classic waveguides with total internal reflection operation, localization is possible only under the light line of course. Figure 5 also indicates that there are three P_2 states localized to the bandgap region. The one that is closest to the middle of the potential well has a high-energy confinement for all wave numbers. More-

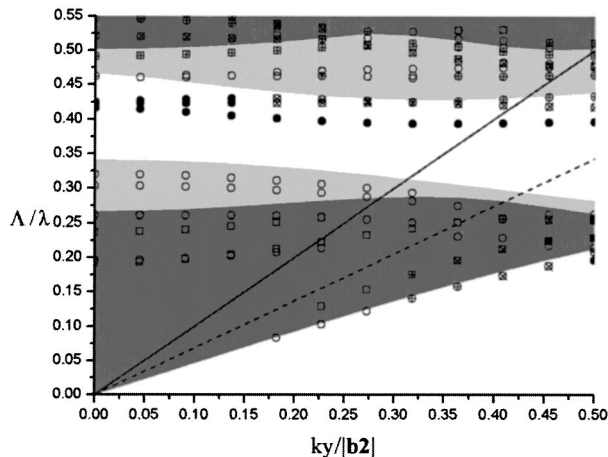


Fig. 5. Band diagram for propagation along the y axis only for a D_{10}^{yz} defect with $r_D = 0.45\Lambda$.

over, a frequency interval with single-mode operation is distinguishable for this defect state. Two P_1 defect states are also present and have been pulled down into the gap region from the top of the gap, unlike for Fig. 4(a). When $|r_0 - r_D|/r_0 \sim 0$ at the point where single-mode operation is facilitated in the defect the localized fundamental mode has a higher effective index than the radiation states on the upper gap edge; because the effective index of the defect material is higher than in the surrounding crystal, the localized defect state emerges therefore at the upper gap edge and is pulled down into the bandgap. Decreasing the defect radius allows this defect state to propagate along the waveguide with better energy confinement, experiencing a higher effective index with a frequency band that moves downward into the gap. The two P_1 defect states in the bandgap have different dispersion properties and energy confinements. One of these shows that positive, zero, and negative dispersion properties are possible in this PC as predicted in past 2D investigations.²⁴

In recent years slowing, trapping, and storage of light in atomic media at specific temperatures that depend on the nature of the atoms were demonstrated.^{25–28} Laser cooling of atoms and electromagnetically induced transparency facilitated by a control laser beam have been used to tune the collective state of the carefully prepared isolated atomic sample. In such experiments the medium is maintained in a coherent state, permitting small group velocities. The control laser beam must experience a lower index of refraction and a higher group velocity than the signal laser beam pulse that is to be stored. The control laser beam is applied to slowly change the collective state of the atomic system while the signal pulse propagates in the medium such that the photonic band of the propagating signal pulse is placed in $(\mathbf{k}, \omega)$ space with (near-) zero group velocity. Photons can be handled similarly in a PC structure in which light experiences a high index of refraction and small group velocities owing to the presence of photonic bandgaps with constructive diffractive interference localizing energy in a defect region. Solid PCs can exhibit unusual dispersion properties at room temperature. Figure 6 shows 2D views in a plane parallel to the xy plane of the E_z field and the in-plane energy flow of localized EH modes at $(k_y/|\mathbf{b}_2|, \omega) = (0.318182, 0.14056)$ and at $(k_y/|\mathbf{b}_2|, \omega) = (0.318182, 0.39345)$ for the band diagram in Fig. 5. The former mode is a traveling wave with a Gaussian distribution of energy and directionally uniform energy flow along the defect, and the latter mode resembles a resonant state in which electromagnetic energy is allowed in the defect but the net energy flow is nearly zero. Strong vortices appear in the pattern of energy flow (Poynting vector) for the mode in the bandgap that has a small group velocity. External thermoelectric forces, mechanically stressing mechanisms, or an internal nonlinear electromagnetic interaction might permit dynamic control of this defect band such that electromagnetic radiation can be trapped, stored, and released on command in volumes of a few units of λ^3 . A photonic analog of the electronic transistor is therefore feasible in a PC. It is worth mentioning that the strongly localized modes of Fig. 4 near the normalized wave-number value 0.5 also are resonant states with

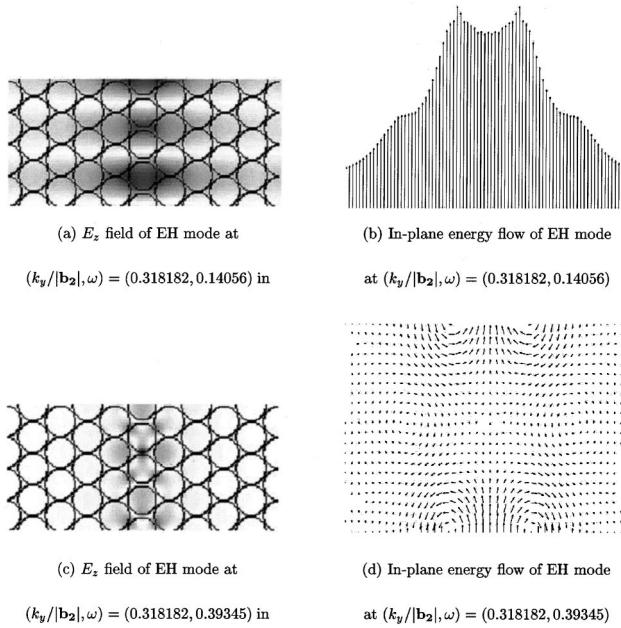


Fig. 6. 2D view in a plane parallel to the xy plane of the E_z field and the in-plane energy flow of a traveling mode and a trapped mode. Vortices appear in the pattern of energy flow (Poynting vector) for the trapped mode in the bandgap that has small group velocity.

small group velocities in which energy is trapped in a flow of rotating vortices in which little net energy flow occurs.

4. DISCUSSION OF IN-PLANE PROPAGATION IN D_{yz}^{yz} AND D_{xz}^{xz} DEFECTS

In the remainder of our analysis we concentrate on defects in a MS2DPC configuration with a large region of forbidden bands for P_1 states but without any frequency region with full gaps for P_2 states. We do so with a MS2DPC with Si and SiN as materials A and B, respectively, of the multilayer stack into which cylindrical air holes are etched in a triangular 2D lattice. The air holes have radius $r_0 = 0.41\Lambda$, $t_{Az} = 0.5\Lambda_z$, $\Lambda_z = 0.4\Lambda$, $n_A = 3.44$, and $n_B = 2.1$ approximately at the $1.55\text{-}\mu\text{m}$ wavelength. We refer to this configuration as MS2DPC1a. Such PCs permit more flexibility in design and manufacture because many material combinations and radii are possible. These PCs exhibit directionally dependent narrow pseudogaps for P_1 states as well as for P_2 states besides the main bandgaps of P_1 states. The following investigation shows that radiation can be guided in planar defects in P_1 states where the P_2 states are considered nonlocalized background states without energy coupling between the two types of orthogonal state in a linear regime of uniform waveguides.

Investigations of propagation parallel to the xy plane in D_{yz}^{yz} and D_{xz}^{xz} defects can help us to understand some of the characteristics of channel defects parallel to the xy plane in configuration MS2DPC1a. The combination of such channel defects with z -invariant channel defects parallel to the z axis permits efficient guiding and manipulation of radiation energy in three spatial dimensions. Channel defects are much easier to design, intro-

duce, and control in a MS2DPC than in 3D PCs with a complex material distribution in the unit cell. An xy -plane-parallel defect can be constructed in the following way: First, a number of periodic units of bilayers A and B are deposited upon a Si substrate. Then lithography is used to etch the channel defects, which are afterward filled with the defect material. A subsequent etching removes unwanted clusters, and a number of periodic units of bilayers A and B are deposited on top of this structure. As a final processing step a 2D PC pattern of holes can be etched through the whole block. We adopt the convention that localized P_1 modes are represented by filled-square symbols and other localized modes that are more generally polarized (P_2 modes) are represented by crosses in the following band diagrams.

Figure 7 shows a band diagram for propagation along the y axis only for a D_{yz}^{yz} defect with $n_D = 1.46$ and $\mathcal{W} = W_D = 1.2\Lambda$. The darker-gray region is a region with all kinds of polarization states, whereas the lighter-gray region is the bandgap for P_1 states propagating along the y axis. For simplicity, small pseudogaps for P_1 states or P_2 states are not shown. The upper solid white line is the upper limit of the regions of omnidirectional reflection relative to air and SiO₂ for P_1 states. The dotted and lower solid white lines are the lower limits of the region of omnidirectional reflection for P_1 states relative to SiO₂

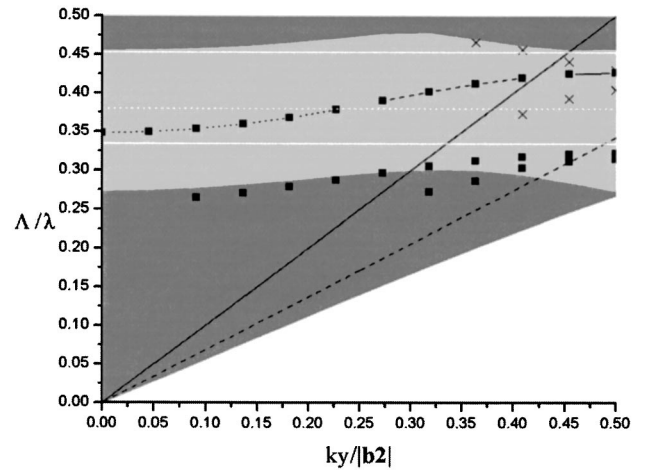


Fig. 7. Band diagram for propagation along the y axis only for a D_{yz}^{yz} defect with $n_D = 1.46$ and $\mathcal{W} = W_D = 1.2\Lambda$. The darker-gray region is a region with all kinds of polarization states; the lighter-gray region is the bandgap for P_1 states propagating along the y axis. For simplicity, small pseudogaps for P_1 states or P_2 states are not shown. The upper solid white line is the upper limit of the regions of omnidirectional reflection relative to air and SiO₂ for P_1 states. The lower dotted and solid white lines are the lower limits of the region of omnidirectional reflection for P_1 states relative to SiO₂ and air, respectively. Filled squares joined by a solid curve, a dashed curve, and a dotted curve represent localized P_1 modes with $\mathcal{E}_C^{W_D} \geq 70\%$, $50\% \leq \mathcal{E}_C^{W_D} \leq 70\%$, and $30\% \leq \mathcal{E}_C^{W_D} \leq 50\%$, respectively; while squares that are not joined by curves represent those with $\mathcal{E}_C^{W_D} \leq 30\%$. Filled squares, P_1 defect modes with relatively high energy localization; crosses, strongly localized P_2 states with $\mathcal{E}_C^{W_D} \geq 30\%$. In the lighter-gray region many nonlocalized P_2 states are present. All localized P_1 defect modes near the main gap are shown.

and air, respectively. The average index of the defect region delimited by $|x| < W_D/2$ lies between those of air and of SiO_2 . Therefore the lower limit of the region of omnidirectional reflectivity for P_1 states is closer to that of air than to that of SiO_2 in MS2DPC1a. Filled-square symbols joined by a solid curve, a dashed curve, and a dotted curve represent localized P_1 modes with $\mathcal{E}_C^{W_D} \geq 70\%$, $50\% \leq \mathcal{E}_C^{W_D} \leq 70\%$, and $30\% \leq \mathcal{E}_C^{W_D} \leq 50\%$, respectively, whereas square symbols that are not joined by curves represent those modes with $\mathcal{E}_C^{W_D} \leq 30\%$. The filled-square symbols represent P_1 defect modes with relatively high energy localization, whereas the crosses represent strongly localized P_2 states with $\mathcal{E}_C^{W_D} \geq 30\%$. In the lighter-gray region many nonlocalized P_2 states are present. All localized P_1 defect modes near the main gap are shown. The black solid and dashed lines are the air and SiO_2 lines, respectively.

The defect in the situation of Fig. 7 exhibits an interesting frequency range of single-mode operation within the region of omnidirectional reflection with respect to P_1 states. Efficient coupling of laser energy with even TE modes into the defect state should be possible. Input-output coupling and mode coupling issues will be subjects of future studies, but, in general, energy pumped into the localized P_1 defect state is not transferred into P_2 states in ideal structures with few impurities and little surface roughness. Such might not be the case when nonlinear phenomena become significant in the defect where electromagnetic fields interfere and interact with molecules of specific resonance frequencies in the region of high-energy localization because atomic excitations and absorption generally are accompanied by stimulated and spontaneous emission of radiation with energy distributed in all allowed modes of the surrounding medium. In free space the excited atom is an isotropic radiator emitting into the continuous spectrum of free-space radiation modes, but in a PC the atom can emit only in a discrete spectrum. The emission of radiation in a nonlinear process might couple energy into P_2 states; however, this coupling might be minimal in a solid state whose constituent atoms or molecules may be locked in a common orientation to give anisotropic emission of radiation and discrete vibrational orientations. The P_1 localized state of Fig. 7 puts the waveguide in single-mode operation within the region of omnidirectional reflection, and any other eventual P_2 state can be eliminated by a relatively sharp bend of the defect with radii of curvature comparable to the wavelength of radiation because of the dependence of the P_2 -mode pseudogaps on directional polarization. The P_1 defect state has a frequency that is an ascending function of the wave number k_y .

Figure 8 is a band diagram for propagation along the x axis only for a $D_{\parallel}^{xz}$ defect with $n_D = 1.46$ for various waveguide widths, where $|y| < W_D/2$: $W_D = 0.8\lambda$ (dotted curves), $W_D = 1.0\lambda$ (dashed curves), and $W_D = 1.2\lambda$ (solid curves). Localized P_1 modes are represented by squares ($50\% \leq \mathcal{E}_C^{W_D} \leq 70\%$), diamonds ($30\% \leq \mathcal{E}_C^{W_D} \leq 50\%$), and downward-pointing triangles ($\mathcal{E}_C^{W_D} \leq 30\%$). P_1 defect states have frequency functions that are descending functions of wave number k_x , unlike in the P_1 state of Fig. 7. For $W_D = 1.2\lambda$ three defect bands

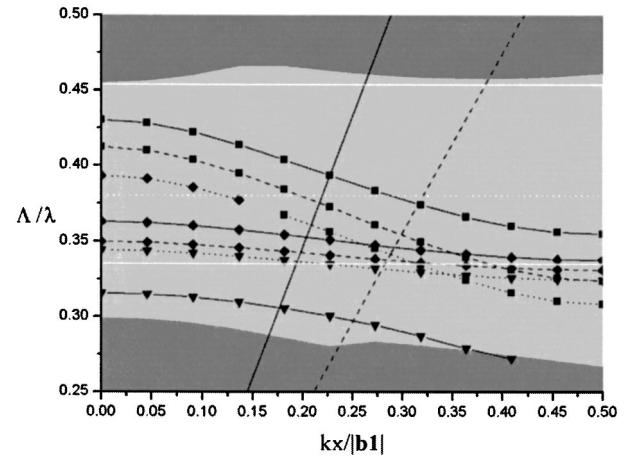


Fig. 8. Band diagram for propagation along the x axis only for a $D_{\parallel}^{xz}$ defect with $n_D = 1.46$ for three waveguide widths: $W_D = 0.8\lambda$ (dotted curves), $W_D = 1.0\lambda$ (dashed curves), and $W_D = 1.2\lambda$ (solid curves). Localized P_1 modes are represented by square symbols ($50\% \leq \mathcal{E}_C^{W_D} \leq 70\%$), diamond symbols ($30\% \leq \mathcal{E}_C^{W_D} \leq 50\%$), and downward-pointing triangles ($\mathcal{E}_C^{W_D} \leq 30\%$).

are present, and single-mode operation in the region of omnidirectional reflection is also possible. The single-mode operation indicates that high-energy transfers about sharp bends should be possible from waveguide channels parallel to the y axis into waveguide channels parallel to the x axis because radiation of P_1 states into the bulk PC is prohibited by the region of omnidirectional reflectivity. In such bends, backward reflections must be minimized by careful design of the branching area in the coupling region where polarization effects and the number of excitable modes are important factors. Filtering signals of different wavelengths should permit wavelength-division multiplexing. The appearance and evolution of defect bands with increasing width are clear from the figure. The defect bands detach themselves from the lower edge of the gap that has a high effective index when W_D is small. As the width is increased, the defect bands move up in frequency, with lower effective index and stronger confinement of energy but narrower bandwidth. A further increase of the width brings further stronger energy confinement in the defect band and a wider bandwidth.

5. DEFECTS WITH BROKEN SYMMETRY IN THE xy PLANE

In making the MS2DPC1a structures and before etching of holes, it is clear that obtaining the waveguide structures that exhibit inversion symmetry requires a quite precise alignment of the buried waveguide's center axis, and a lithographic mask with a hole pattern is required. Following the investigations described in Section 4 it is natural to investigate the significance of a break in symmetry caused by the misalignment of the waveguide center axis and a chosen in-plane axis of the 2D crystal lattice of holes. Figure 9 shows a 2D view of the supercell with a yz plane defect in the MS2DPC1a structure under

investigation. This defect is created by introduction of a layer of SiO_2 material in a region determined by $|x - \sqrt{3}\Lambda/4| \leq W_D/2$ in the multilayer stack before the lattice of holes is etched in the structure. Inversion symmetry is broken because of misalignment.

Figure 10 shows a band diagram for propagation along the y axis only for a D_{yz}^y defect with $n_D = 1.46$ and $W_D = 1.2\Lambda$ for a structure with symmetry breaking with the defect restricted to $|x - \sqrt{3}\Lambda/4| \leq W_D/2$ (filled downward-pointing triangles) and a structure without symmetry breaking with the defect restricted to $|x| \leq W_D/2$ (filled squares). Symmetry breaking has a significant influence on the dispersion of the P_1 defect states because of the different positioning of air hole scatterers in the waveguiding defect. If the waveguiding defect is made from a section without symmetry breaking that gradually changes into a structure that breaks symmetry, the energy carried by the initial single mode will be distributed into two defect states with different effective energy-propagation velocities, and a part of the frequency spectrum can be reflected backward if it is initially excited. For large wave numbers near the lower limit of the SiO_2 region of omnidirectional reflectivity (Fig. 10, dotted white line) negative, zero, and positive dispersion is possible.

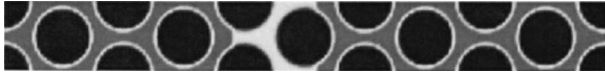


Fig. 9. 2D view of the supercell with a yz -plane defect in the MS2DPC1a structure under investigation. This defect is created by introduction of a layer of material with refractive index n_D in a region determined by $|x - \sqrt{3}\Lambda/4| \leq W_D/2$ in the multilayer stack before the lattice of holes is etched in the structure. Inversion symmetry is broken because of misalignment.

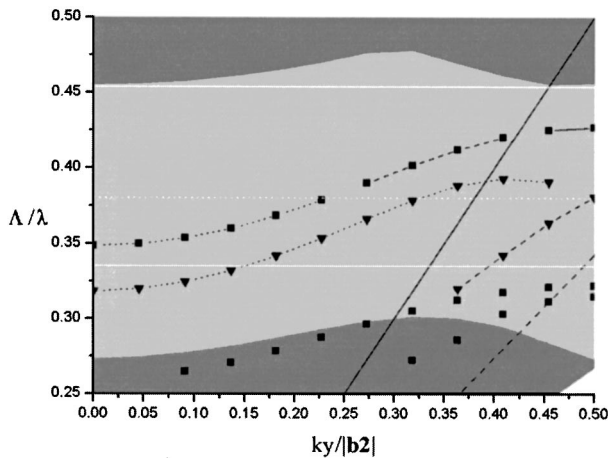


Fig. 10. Band diagram for propagation along the y axis only for the P_1 modes of a D_{yz}^y defect with $n_D = 1.46$ and $W_D = 1.2\Lambda$ for a structure with a symmetry break with the defect restricted to $|x - \sqrt{3}\Lambda/4| \leq W_D/2$ (filled downward-pointing triangles) and for a structure without a symmetry break with the defect restricted to $|x| \leq W_D/2$ (filled squares). Localized P_1 states are represented by symbols joined by a solid curve ($\mathcal{E}_C^{W_D} \geq 70\%$), a dashed curve ($50\% \leq \mathcal{E}_C^{W_D} \leq 70\%$), and a dotted curve ($30\% \leq \mathcal{E}_C^{W_D} \leq 50\%$). Symbols that are not joined by curves represent states with $\mathcal{E}_C^{W_D} \leq 30\%$.

6. CONCLUSIONS

Bragg stacks of planar photonic crystal slabs can exhibit large bandgaps, and investigations have shown that radiation can be localized efficiently into planar defect regions bounded by parallel planar walls perpendicular to the stack surface in these rather simple crystals. Polarization states with less than 10% of their electric energy oscillating in the component along the surface normal of the stack can be localized most efficiently because they experience higher localization in many material systems. The multilayer PC slabs provide a full in-plane bandgap, unlike single PC slabs. It has been shown that high degrees of confinement are possible, together with flexible tailoring of group velocities and dispersion in several directions. The dependence of the energy flow on waveguide orientation in the crystal has been demonstrated, and the significance of in-plane symmetry breaking has been clarified. Single-mode operation and near-zero group velocities are possible, permitting the slowing, trapping, and storage of electromagnetic radiation. The storage of radiation has been illustrated by strongly localized vortices in the energy flow (Poynting vector), indicating the presence of a state in the condensed matter where energy is localized to the defect but where no net energy flow occurs. Some advanced photonic manipulations are feasible in cavity defects filled with low- and high-index materials within Bragg stacks of photonic crystal slabs.

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